



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification ⁶ : H02P 6/08, 6/10</p>	<p>A1</p>	<p>(11) International Publication Number: WO 97/25767</p> <p>(43) International Publication Date: 17 July 1997 (17.07.97)</p>
<p>(21) International Application Number: PCT/GB97/00052</p> <p>(22) International Filing Date: 9 January 1997 (09.01.97)</p> <p>(30) Priority Data: 9600549.1 11 January 1996 (11.01.96) GB</p> <p>(71) Applicant (for all designated States except US): LUCAS INDUSTRIES PUBLIC LIMITED COMPANY (GB/GB); Stratford Road, Solihull, West Midlands B90 4LA (GB).</p> <p>(72) Inventors; and (75) Inventors/Applicants (for US only): COLES, Jeffrey, Ronald [GB/GB]; 64 Kineton Green Road, Olton, Solihull, West Midlands B92 7EB (GB). JONES, Russell, Wilson [GB/GB]; 6 Montgomery Close, Shottery, Stratford-upon-Avon, Warwickshire CV37 9EU (GB). WILLIAMS, Andrew, James, Stephen [GB/GB]; Meadow Springs, Mill Lane, Lapworth, Solihull, West Midlands B94 6HX (GB).</p> <p>(74) Agent: BARKER, BRETTELL & DUNCAN; 138 Hagley Road, Edgbaston, Birmingham B16 9PW (GB).</p>		<p>(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).</p> <p>Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</p>
<p>(54) Title: MOTOR DRIVE CONTROL</p> <div data-bbox="451 1142 1198 1675"> </div> <p>(57) Abstract</p> <p>A control strategy for a multiple phase brushless motor (1) is disclosed in which the top (2, 3, 4) and bottom (5, 6, 7) switching devices in two arms of the motor bridge are driven using complementary pulse width modulated waveforms, so that the top device (2, 3, 4) in one of the arms is in the ON state whilst the bottom device (5, 6, 7) is in the OFF state and vice versa. In an alternative arrangement, the control strategy described hereinbefore is used at high motor speeds whilst at low motor speeds a conventional modulation scheme is used in which a top switching device (2, 3, 4) in one arm of the bridge is in the ON state and a bottom device (5, 6, 7) in a different arm of the bridge is pulse width modulated. In another aspect, a method of calculating the position of the motor rotor is disclosed.</p>		

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MOTOR DRIVE CONTROL

This invention relates to improvements in electrical motor control strategies, especially but not exclusively for use in an electrical power steering system.

It is known in the art to provide an electrical power steering system for vehicles in which an electrical motor replaces the traditional hydraulic assistance, so as to produce a compact, efficient steering system. Steering assistance is provided by driving the motor in response to a measure of the torque in the steering column. In such an application, it is essential to have good control of the output characteristics of the motor, i.e. the motor torque.

A typical motor and drive circuitry of the kind to which this invention relates, and which may be used in a power steering system, comprises three elements; a multiple phase permanent magnet brushless motor in which the phases are connected in a star fashion, a multiple phase bridge, each arm of the bridge comprising a top switching means and a bottom switching means; and sensing means for detecting rotor position and/or motor current. The top and bottom switching means typically each comprise a single transistor or two or more transistors connected in parallel.

The control strategy controls the modulation technique used to drive the transistors, thereby controlling the current in the motor windings together with knowledge of rotor position and hence controlling the motor torque.

Traditionally, such a motor system is driven by a dedicated integrated circuit which performs the function of the control strategy, for example the Motorola MC33035 integrated circuit (IC). This provides all the features necessary to implement a motor control strategy for a 3 or 4
5 phase motor. The IC provides 3 outputs for driving the top transistors, and 3 outputs for driving the bottom transistors in each arm. For any given rotor position, the IC is used to enable only one top and one bottom transistor of the drive circuitry. An additional feature of this type of motor control is that the enabled top and bottom transistors are on
10 different arms of the bridge.

In the enabled state, the bottom transistor only is pulse width modulated, with the enabled top transistor being in the ON state for the whole modulation period. Varying the pulse width modulation duty of the
15 bottom transistor determines the motor voltage and can be used to control motor current level and speed. The selection of the desired top and bottom transistor is performed under the IC's simple control strategy which interprets the data from a position sensor in conjunction with measurements of the current flowing in the motor windings. This type of
20 modulation will be referred to as bottom only modulation, because only the bottom transistors are pulse width modulated.

A disadvantage of the conventional commutation including the bottom control as described above is that in open loop voltage control
25 mode, a transient drop in overall resultant motor current level (and hence torque) occurs upon commutation from one phase to the next. In the power steering application set forth, these transients are felt by the driver through the steering wheel. Other problems arise when the motor is changing direction, due to poor current control using bottom-only
30 modulation when the motor decelerates.

An aim of the present invention is to provide an improved motor control strategy which provides accurate control of motor torque irrespective of rotor speed and position, to minimise motor torque ripple
5 and to minimise acoustic noise from the motor.

According to a first aspect of the invention, in a control strategy for controlling the pulse width modulation of a multiple phase brushless motor having at least three phases in which each phase of the motor is
10 connected to an arm of a multi-phase bridge and each arm of the bridge comprises a top switching device and a bottom switching device, said switching devices comprising at least one transistor,

said control strategy is characterised by comprising driving the switching means with a first modulation mode in which complementary
15 pulse width modulated inputs are applied to the top and bottom switching devices in two arms of the bridge so that in each of said two arms the top switching device is in the ON state whilst the bottom device is on the OFF state, and at the end of the pulse width modulation duty cycle the state of the two switching devices is reversed,

20 selection of said pulse width modulation duty cycle and which switching devices are modulated being performed by a control algorithm in response to the output of a sensing means.

In this control strategy, the pulse width modulated inputs applied to
25 the top and bottom transistors in a given arm of the bridge are complementary to one another, i.e. during a single modulation period, one transistor is ON whilst the other transistor is in the OFF state, and at the end of the pulse width modulation duty within the modulation period, the state of the two transistors is reversed. The average voltage applied to
30 the motor is then determined by the ratio of the ON times of the two

transistors. The state of the two transistors therefore swaps during each modulation period.

This modulation technique will be known as complementary modulation, as the transistors in each arm of the bridge are energised as the complement of each other. The direction of the applied motor voltage is reversed on each PWM cycle. Zero net motor voltage is applied at 50% PWM duty when forward voltage is applied for the same time as reverse voltage, and there is no discontinuity of the bridge operation upon reversal of net applied motor voltage. In this manner, control difficulties experienced in the bottom only modulation technique are eliminated, and smooth reversals of the steering wheel can be achieved when used in an EPAS system. Also, by using complementary mode switching the commutation transients are symmetrical for both positive and negative half cycles of motor current, whereas this is not true in the case of lower or bottom-only control.

Preferably, an interlock delay can also be provided if this feature is not provided in the driver IC for each transistor.

20

The addition of an interlock delay prevents "shoot-through". Shoot-through occurs when a top and bottom transistor in the same leg of the bridge are both turned on. MOS-FET and other transistors take a finite time to turn on and off so the interlock delay can be used to delay turning on of the bottom transistor after turning off the top transistor (or vice versa).

25

Preferably, the sensing means may comprise a current sensor for detecting the current flowing in the motor, and an angular position sensor

for detecting the rotor position of the motor rotor, the outputs of both sensors being employed by the control algorithm.

In this case, the motor current is controlled by reading the current
5 sensors, processing the measured values in accordance with the output of
the position sensors to provide a 'motor current' value, applying an
appropriate feedback control algorithm that compares this 'motor current'
to a demanded value in software, and adjusting the PWM duty in
accordance with the output from the control algorithm. The PWM duty is
10 applied to the appropriate transistors of the bridge according to the output
of the angular position sensors.

Preferably, the motor may comprise a 3-phase motor and a 3-phase
bridge will then be used.

15

Hall effect devices can be used as the position sensors, and may be
arranged in a manner that enables the output of the hall sensors to be
expressed as a 3-bit digital code. This digital code can then be employed
by the control strategy when determining which transistors will be pulse
20 width modulated.

In the complementary PWM mode, just two of the motor phases
may be energised at any given rotor position except for commutation
transients when all 3 phases conduct for a short period, typically the same
25 two phases as would be used in the bottom only modulation technique. In
this way, it is not necessary to use costly high resolution position sensors.

Whilst the above modulation scheme offers a considerable
improvement over the bottom only modulation technique during motor

reversals, a disadvantage of the complementary scheme is that it generates a higher ripple current in the bridge filter capacitor.

Therefore, according to a second aspect of the invention, we
5 provide a control strategy for controlling the pulse width modulation of a multiple phase brushless motor having three phases in which each phase of the motor is connected to an arm of a multi-phase bridge and each arm of the bridge comprises a top switching device and a bottom switching device, said switching devices comprising at least one transistor,

10 characterised in that said control strategy selects from a first modulation mode and a second modulation mode:

whereby in said first modulation mode, the top switching device and the bottom switching device in at least one arm of the bridge are driven by complementary pulse width modulated inputs applied to the top
15 and bottom switching devices so that one of the said top or bottom switching devices is in the ON state whilst the other one of the top or bottom switching device is in the OFF state, and at the end of the pulse width modulation duty cycle, the state of the two switching devices is reversed;

20 and whereby in said second modulation mode, a pulse width modulated input is applied to a bottom switching device in one of said arms of said bridge whilst a top switching device in a different one of said arms of said bridge is switched ON, selection of the pulse width modulation duty cycle and which switching devices are modulated being
25 performed by a control algorithm.

Preferably, the control algorithm employs the information from the sensing means to determine the most suitable modulation technique.

Preferably, complementary modulation is used at low motor speeds to give good control of motor reversals, and bottom only PWM is used at high motor currents to minimise the ripple current in the bridge filter capacitor. The control algorithm may switch motor drive from one mode
5 to the other at a motor current of approximately half the maximum motor current.

The current flowing in ground return from the bridge and in each of the motor phases and/or the individual phase legs can be sensed by
10 means of the potential drop across a series resistor in these paths.

A third aspect of the invention is the implementation of a soft commutation mode or a hard commutation mode when either complementary modulation or the bottom only modulation is selected by
15 the control algorithm.

In a soft commutation mode, the rate of the decrease of the terminating phase current is decreased to match the rate of increase of the commencing phase current. This offers the advantage of maintaining the
20 current in the third phase at a constant level without the undesirable current transient that otherwise occurs due to inductive effects. The reduced rate of change at the commutation point reduces the magnitude of the induced EMF's in the motor phases and also reduces acoustic noise.

25 Preferably, the duration of the soft commutation is controlled by the control algorithm in response to motor current and rotor position so as to optimise performance at low rotor speed and to minimise the drop in motor torque at high rotor speed.

Alternatively, hard commutation may be employed. In this case, the rate of increase of the commencing phase current is increased to match the rate of decrease of the terminating phase current to maintain a constant current in the third phase, and again overcoming the undesirable
5 momentary drop in current (and hence torque) that otherwise occurs. The duration of such a hard commutation may be controlled by the control algorithm or in software.

A second aim of the present invention is to provide a means for
10 determining the absolute position of the rotor of the motor, enabling further improvements in detection and control of the commutation event.

According to a fourth aspect of the invention, a method of calculating the position at a moment in time of a motor which is connected
15 to an output shaft through an intermediate means comprises the steps of:

obtaining a first measurement of actual rotor position at a first instance in time using sensing means provided at the motor;

calculating speed of rotation of said output shaft using a sensing means provided on said output shaft;

20 calculating an offset indicative of the displacement of the rotor of the motor between the first instance of time and said moment in time based upon the speed of rotation of the output shaft, and;

modifying the first measurement of rotor position obtained at the first instance by adding the offset to produce an output indicative of
25 absolute motor rotor position at said moment in time.

Preferably the motor position sensing means comprises a high precision absolute motor position sensor.

Alternatively the motor position sensing means comprises a combination of position measurements from sensing means on the output shaft with the output of position sensors on the motor.

- 5 Alternatively the motor position sensing means comprises a combination of absolute position sensor on the output shaft with an incremental position sensor on the rotor of the motor.

10 Preferably, the motor position sensor may comprise Hall effect sensors, which may produce a 3-bit digital code. In the case of an electrical power steering system, for example, the intermediary means may comprise a clutch and/or a gearbox, and the motor may drive the output shaft through a worm and worm wheel.

15 The position of the output shaft, which in the case of an electrical power steering system would be the steering column, can be obtained from a dedicated position sensor or from a suitable output from a torque sensor, such as the Lucas Linear Array Torque sensor.

20 The rotor position sensors, i.e. Hall effect sensors, provide an absolute indication of motor electrical angle. Whenever a Hall sensor changes state, an offset is set to zero. On every periodic sample, the output shaft velocity can be determined from the output shaft position sensor. This may be done by comparing the last two shaft position
25 measurements. The gearbox ratio may be multiplied by the shaft velocity and added to this offset. The Hall effect state plus the offset enables high resolution absolute position information to be determined.

30 In this manner, by resetting the offset on every Hall sensor transition the effects of backlash and torsional wind-up is minimised, and

so that the position information on the output shaft can be used to indicate the position of the motor rotor.

According to a further aspect of the present invention, absolute
5 angular position information can be used to optimise the motor commutation position under different motor operating conditions.

The commutation position may be varied by advancing or retarding the position at which a commutation event occurs, in response to the
10 absolute motor position readings. This minimises the torque step that can occur at the commutation point, due to changes in the magnetic effects in the motor as current levels increase. The commutation point can also be varied as a function of the motor speed to provide higher torque at higher motor speeds, thus improving the steady state torque/speed envelope of
15 the motor for a given battery voltage.

The demanded current may also be controlled in order to minimise predictable on-load motor torque ripple by adjusting the current in response to motor current, motor velocity and absolute position
20 information.

Some embodiments of our invention are illustrated in the accompanying drawings in which:-

25 **Figures 1a and 1b** show a 3-phase brushless DC motor and associated power drive circuitry which comprises a 3-phase bridge;

Figure 2 shows the bottom only modulation technique used and the current state of each transistor for a given Hall sensor and
30 code;

Figure 3 illustrates the complementary PWM strategy according to a first aspect of the invention;

5 **Figure 4** illustrates the two PWM1 and PWM2 signals;

Figure 5 illustrates a comprehensive control strategy which employs complementary and bottom only modulation according to the second aspect of the present invention;

10

Figure 6 shows the Hall sensor code changes which result in top commutation;

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Figure 7 shows the Hall sensor code changes which results in bottom commutation;

Figure 8 shows an example of the bottom soft commutation strategy;

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Figure 9 shows an example of a control routine for implementing bottom soft commutation;

Figure 10 shows an example of the top soft commutation strategy;

25

Figure 11 shows an example of a software control routine for implementing top soft commutation strategy;

Figure 12 illustrates the relationship between Hall effect sensors and the motor armature such that rotor position information can be obtained;

5 **Figure 13** illustrates schematically an electrical power steering system which embodies the control strategy of Figure 5;

Figure 14 (a) and (b) illustrates the use of current shaping by applying a boost voltage to minimise position dependent ripple; and

10

Figure 15 shows the relationship between the transient dip in current in the positive A and negative B cycles for (a) the complementary and (b) bottom only modulation schemes.

15 It is well known that the instantaneous torque in a permanent magnet excited electric motor can be controlled so that it is substantially proportional to the instantaneous motor current in the excited phases. Hence, controlling the motor current also controls the motor torque. Since it is cheaper to measure motor current than to directly measure
20 motor torque, a current control system is implemented.

A specific embodiment of a motor and power drive circuitry is shown in Figure 1. The motor (1) shown is a three-phase brushless DC motor, the phases of the motor being connected together in a star
25 configuration. The drive circuitry comprises a three phase bridge. Each arm of the bridge further comprises a pair of transistors connected in series between a supply rail and a ground, with the motor windings being tapped off from between the two transistors. MOS-FET type transistors are used. The transistors in each arm are referred to in this text as top
30 transistors (2,3,4) and bottom transistors (5,6,7) respectively.

This type of motor and drive circuit is often controlled using a dedicated IC such as Motorola MC 33035 that switches one top field effect transistor (FET) fully on, and applies a pulse-width modulated (PWM) control signal to one bottom FET. The particular FETs are determined by the IC which decodes information from an angular position sensor in conjunction with current information.

In one example, the angular position of the motor rotor is sensed through use of magnetic effect sensors placed so as to detect the passing of an overhang section of the rotor magnets wherein the sensor is arranged to have a magnetic shield that provides a magnetic path for the sensor circuit itself whilst shielding the sensor from the effects from any external magnetic fields.

In operation the sensing element switches each time a magnetic circuit is made or broken which occurs as a pole of the motor or rotor magnet 27 passes a sensing element. This switching signal is passed via connections, not shown, to the motor control circuit.

The rotor carries a back iron sleeve 26 having magnets 27 secured around its periphery covered by a rotor sleeve 28. A clearance or air gap 29 is provided to allow the rotor to move angularly with respect to the sensor assembly 30 and motor stator (not shown).

The sensor assembly shown in Figure 12 is a three element device surrounding an arc or outer section of the rotor. The size and number of elements 31 within the sensor assembly may vary between 1 and any number covering the entire circumference of the rotor, depending upon the configuration i.e. the number of rotor pole pieces of the motor.

The sensor assembly comprises a non-magnetic sensor carrier 32 in which are placed the magnetic sensing elements 31. This is surrounded by a magnetic sensor back iron 33 which acts to enhance the magnetic field strength around the sensing elements to aid switching and eliminate magnetic interference, and importantly to provide the sensor assembly with its mechanical robustness, as typically the materials from which a suitable non-magnetic sensor carrier would be made are low in mechanical strength.

10

The output signal from the Hall-effect sensing means can be adapted to provide a 3-bit digital code. The need for the 3-bit code is optional, and used in the preferred embodiments disclosed in this application by way of example only. At least one or more sensors providing one or more bits of position information could be used subject to the design and performance and fault tolerance constraints imposed on the actual working application.

Information about the motor current is obtained by measuring the current flowing in ground return from the bridge and/or in each of the 3 motor phases.

In Figure 1b, only a single sensing resistor 8 is shown. Measuring the current flowing in the resistor can be performed by way of measuring the potential drop across the resistor and applying Ohm's Law. This single resistor provides information on the current flowing in ground return from the motor.

Alternatively, a resistor 8a,8b,8c can be provided for each arm of the bridge as shown in Figure 1b. This allows the current in each phase to be measured, i.e. phase leg sensing.

5 Both the current and position information can be used by the control strategy as below.

The motor current is controlled by reading the current sensors, processing the measured values in accordance with the 3-bit digital code
10 from the Hall-effect sensors to provide a motor current value, applying an appropriate feedback control algorithm that compares this "motor current" to a demanded value in software, and adjusting the PWM duty in accordance with the output from the control algorithm. The PWM duty is applied to the appropriate transistors of the 3-phase bridge according to
15 the 3-bit digital code from the Hall effect sensors. This method of motor control is advantageous as it requires fewer components than electronic hardware, assuming that the microprocessor is already present.

One form of motor modulation technique which can be used with
20 the above control strategy is known as bottom-only PWM modulation, as in all motor control circumstances only the bottom transistors 5,6,7 are pulse width modulated, whilst the top transistors 2,3,4 are either in the ON state or the OFF state, as determined by the control strategy. Figure 2 shows a bottom-only modulation scheme showing the state of the
25 transistors in each arm of the bridge for a given Hall effect switch code. It can be seen that in this modulation technique, only a single modulation channel, PWM1, is required.

A disadvantage of the above control strategy, in which conventional
30 commutation is employed, is that there is a transient drop in the motor

current (and hence torque) in the uncommutated phase upon commutation of the other two phases. This originates from attempting to enforce fast changes of current in the inductive windings of the motor. This transient drop in motor torque, which occurs upon commutation, can be felt and
5 heard at the steering wheel when the motor is operating in an EPAS system.

A further disadvantage of the bottom-only PWM technique is that it provides poor control of current when the motor is reversed. The most
10 important reversal is one in which the motor current sign is changed so that instead of putting mechanical power into the steering system, the motor is taking mechanical power out of the steering system (that is, braking the movement of the output shaft). Under such reversals, it is difficult to accurately control the motor current with bottom-only PWM.

15

This is because the bridge has a non-linear response under such a reversal. When the motor is braking, regenerative currents are generated in the motor windings. With bottom-only switching, these regenerative currents can only flow when the bridge is reversed (i.e. when the top
20 transistors are switched). Thus when the bridge is reversed, the regenerative current starts to flow very suddenly causing a sharp change in motor current (and hence motor torque). Such a sharp change in torque is undesirable.

25 In an EPAS system it is essential to have good current control under motor reversal and the motor current is often reversed with the motor moving (and hence braking).

Figure 3 provides details of an example of an alternative PWM
30 mode known as complementary PWM mode which forms a first aspect of

this invention. It is known as complementary PWM because the transistors are pulse width modulated as the complement of each other using complementary PWM signals. In this modulation scheme, the direction of the applied motor voltage is reversed every PWM cycle. It
5 can be seen, therefore, that the transistors are energised as a complement to each other, and both the top and bottom transistors can be modulated. It can be seen that two PWM channels, PWM1 and PWM2 are needed.

The two PWM channels have detail characterising features as
10 shown in Figure 4. PWM-PERIOD 50 is the total time of one modulation cycle. PWM1-HIGH-TIME 51 is the duty time that PWM1 is high (i.e. transistor turned 'ON') and PWM2-HIGH-TIME 52 is the time that PWM2 is high (i.e. transistor turned 'ON'). In normal complimentary operation, the two channels are complimentary and only one transistor is
15 on at a time, the transistors swapping over every during each modulation period. An INTERLOCK delay 53 is also provided to prevent shoot through.

In operation, zero net motor voltage is applied at 50% PWM duty
20 when forward voltage is applied for the same time as reverse voltage. Thus, in this mode there is no discontinuity of bridge operation upon reversal of net applied motor voltage and hence no torque transient is generated. This results in smooth reversals of the steering wheel.

25 A similar PWM, mode is commonly employed in AC brushless drives, where a 'flux' vector is established by energising all three motor phases to a different degree. However, this requires a high resolution position sensor which is costly. In the complementary PWM technique, only two phases are energised at a given rotor position, and so low

resolution position information, such as the 3-bit code generated by the Hall sensors, can be employed.

The complementary PWM technique offers the advantage that the
5 transients which occur during bottom only modulation are eliminated. However, a disadvantage of the complementary modulation technique is that it generates higher ripple current in the drive circuit than the bottom only modulation.

10 In view of the disadvantages and advantages between the two PWM modes, the control strategy shown in Figure 5 employs a combination of bottom only modulation and complementary modulation. Complementary modulation is selected for currents of low value either side of zero (e.g. ± 10 amps) to give smooth control of motor reversals. Bottom only
15 modulation is then switched in by the control strategy for higher currents to minimise current ripple in the drive stage. Switching between the two is performed by the control algorithm in connection with the current sensing means. This dual modulation control strategy forms the second aspect of the invention.

20

Figure 13 illustrates an electrical power steering system which incorporates a motor control strategy of the kind illustrated in Figure 5. An electronic control unit 34 is adapted to receive signals from an ignition switch 35, vehicle speed signalling means 36 diagnostic means 37, CAN
25 interface means 38, and torque sensor electronic means 39. The electronic control unit 34 operates on the various signals and emits an energising current to control the power assistance applied to a steering mechanism 40.

As illustrated a steering wheel 41 controls the operation of a steering linkage 42 through a column shaft 43. The torque applied to the column shaft 43 is augmented by an electric actuator 44 under the control of the energising current from the electronic control unit 34.

5

Figure 5 illustrates various logical means, in software terms, that would be embodied within the controller shown in Figure 13. In this control strategy, both complementary 9 and bottom only 10 modulation are employed.

10

Complementary modulation is used at low motor currents, typically up to half the maximum motor current. If the output from the current sensing means shows that the current exceeds a pre-set value, bottom only modulation is employed. The control strategy will switch modulation
15 back to complementary modulation if the current falls back below this pre-set value.

The control strategy when bottom only modulation is selected, employs either bottom soft commutation 11 or top soft commutation 12.
20 Selection of the correct commutation strategy is performed in response to whether a bottom commutation or a top commutation occurs. On completion of either the top or bottom commutation event, the control strategy returns to normal bottom only modulation 10.

25 The control strategy can also switch directly back to complementary modulation from either the bottom soft commutation 11 or top soft commutation 12.

In bottom-only modulation, two types of commutation event can
30 occur. A top commutation occurs when the Hall sensors change state

resulting in one top FET turning off and a different top FET turning on. The Hall sensor code changes when this form of the commutation occur as shown in Figure 6.

- 5 A bottom commutation occurs when one bottom FET is turning off and a different bottom FET is turning on. The Hall sensor code changes when this form of commutation occurs are shown in Figure 7.

10 In order to understand the purpose of the two forms of soft commutation, the behaviour of the motor under a normal commutation must be appreciated. The commutation event consists of terminating the current flow in one motor phase, commencing an equivalent current flow in a second motor phase and maintaining a nominally constant current in a third motor phase. Since the three motor phases are connected in a star
15 configuration to a star point, the sum of the currents flowing in the three phases must remain at zero. However, the rate of increase of the commencing phase current is less than the rate of decrease of the terminating phase current, and so the third (normally constant) phase current drops momentarily, whilst maintaining a value that makes the sum
20 of the three phase currents equal to zero. This drop corresponds to a transient drop in motor torque.

 One solution is to increase the rate of increase of the commencing phase current so as to match the rate of decrease of the decreasing phase
25 current to maintain a constant third phase current and hence a constant motor torque. This is referred to as hard commutation.

 This hard commutation effectively uses a 'voltage boost' feature whereby the PWM duty is increased for a short period while commutation
30 transients are present. In bottom only mode the current transient dip in

the uncommutated phase are not symmetrical for both positive and negative directions of current in the phase. This is shown in Figure 15. Therefore a different level of voltage boost is required to minimise the current dip depending on the direction of current. In complementary
5 mode the dip in the uncommutated phase is the same for both directions of current flow and therefore only one level of voltage boost is needed for a given current level in either direction.

Another solution is to seek to decrease the rate of decrease of the
10 terminating phase current to match the rate of increase of the commencing phase current. When the two are matched, the resulting current in the third phase remains constant during the commutation event and hence the motor torque also remains constant. This solution is referred to as soft
commutation.

15

Figures 8 and 10 show the control strategy employed in order to effect bottom soft and top soft commutation in response to the Hall sensor output code changes during bottom only modulation.

20 In a refinement of the bottom soft and bottom hard commutation techniques, the duration of the commutation, i.e. the number of PWM cycles over which the commutation is effected, is adjusted under software control. This allows the commutation function to be optimised at low rotor speeds and minimises the drop in motor torque at high rotor speeds.
25 This is illustrated in Figures 8 to 11 for the case of soft commutation.

The soft and hard commutation techniques can be implemented by varying the pulse width modulation period PWM2-HIGH-TIME. In the case of bottom soft and top soft commutation, the value of PWM2-HIGH-

TIME can be varied according to the control strategy in response to motor torque and velocity.

An example of the implementation of bottom soft modulation in this manner is shown in Figures 8 and 9. On entry to the bottom soft modulation state, PWM2-HIGH-TIME is initialised to the same value as PWM1-HIGH-TIME. It is then progressively reduced to zero over a predetermined number of PWM cycles. The number of PWM cycles is thus determined by the control unit according to the motor operating conditions.

In the example provided in Figure 9, the control strategy bottom soft commutation sub routine determines the number of PWM cycles over which PWM2-HIGH-TIME is reduced as follows. After initialising PWM2-HIGH-TIME 13, the control strategy checks to see if the next PWM cycle has been reached 14. When the next cycle is reached, the control strategy moves onto the next step which is to determine whether or not a commutation has occurred 15. If a commutation has occurred, the bottom soft commutation routine is exited 18. If commutation has not occurred, however, PWM2-HIGH-TIME is reduced 16 by an amount which is dependent upon the motor torque and the motor velocity. If, after this reduction, PWM2-HIGH-TIME is less than or equal to zero 17, the bottom soft commutation mode is exited. If PWM2-HIGH-TIME is still greater than zero, the routine returns to check whether the next PWM cycle has been reached 14. This is repeated until PWM2-HIGH-TIME is equal to or less than zero and bottom soft commutation is exited.

The bottom soft commutation state is exited normally when PWM2-HIGH-TIME reaches zero, and the rising edge of PWM1 and the falling edge of PWM2 remains synchronised at all times.

A similar modulation technique can be implemented for the top soft commutation, shown in Figures 10 and 11. In this case, PWM2-HIGH-TIME is initialised to the same as PWM-PERIOD on entry to this state.

5 It is then progressively reduced to zero over a predetermined number of PWM cycles. As in the case of bottom soft commutation, the number of cycles is predetermined and exit from this state occurs when PWM2-HIGH-TIME reaches zero. The rising edge of PWM1 and the falling edge of PWM2 remain synchronised.

10

Figure 11 provides an example of a top soft commutation subroutine, expressed in terms of the logical means in software terms that could be embedded within a control strategy in order to implement top soft commutation. After first setting the PWM mode to top soft commutation. After first setting the PWM mode to top soft commutation 19, PWM2-HIGH-TIME is initialised to the same value as PWM1-HIGH-TIME 20. The control routine then checks whether the next PWM cycle has been reached 21. If not, the routine remains in this state until the next cycle is reached, whereupon the control routine enquires whether a commutation has occurred 22. If a commutation has occurred, top soft commutation is exited 25. If no commutation has occurred, the rate of PWM2-HIGH-TIME is reduced 23 by an amount dependent upon the motor torque and the motor velocity. The control routine then checks 24 to see if the new value of PWM2-HIGH-TIME is equal to or less than zero. If yes, top soft commutation is exited, but if 25 the new value is greater than zero, the routine returns to the state where it waits for the next PWM cycle to be reached 21.

In another refinement to the motor control strategy, high resolution absolute motor rotor position measurements can be employed to enable the control system algorithm to optimise the rotor position at which the motor 30

current is switched from one set of phase windings to another, i.e. the position of each commutation.

Typically, the position of the rotor at which commutation occurs is
5 determined by the position of the Hall sensors, commutation being
initiated by a change in the Hall sensor output code. Because the Hall
sensors are attached to the stator, these commutation positions are fixed.
Under certain conditions the motor performance can be improved by
physically moving the commutation positions with respect to the stator,
10 which can help to reduce or eliminate torque discontinuities which arise at
commutation. As the motor current rises, the electromagnetic field of the
stator distorts the magnetic field of the rotor. This distortion effectively
shifts the working angle of the phase. The distortion can be compensated
by advancing the commutation point in the direction of the motor torque.
15 The amount of advance needed depends on the magnitude of the motor
current and when the motor current is negative the advance is also
negative (i.e. a retardation).

Figure 14 (a) and (b) shows how motor current variations can be
20 minimised through the application of a current shaping technique.
Figure 14(a) shows the motor torque without shaping. In Figure 14 (b), a
voltage boost signal is applied to the motor, this signal being the mirror
image, or inverse, of the motor torque ripple which would occur without
smoothing (i.e. torque shown in Figure 14 (a)). The resultant motor
25 current in this case is nominally free of ripple because it is the sum of the
position dependent current and the applied boost signal, as shown in
Figure 14 (b).

The commutation point can also be varied as a function of motor
30 speed to provide higher torque at high motor speeds and thus improving

the steady state torque/speed envelope of the motor for a given battery voltage.

Using high resolution absolute motor position data, the
5 commutation point can be changed under software control. This allows the optimum commutation position to be selected for each motor operating condition.

High resolution position information can be provided by using the
10 Hall effect switches in conjunction with an angular position measurement obtained from a torque sensor provided in the EPAS system to provide steering torque data. The operation of this absolute position measurement is described in the following paragraphs.

15 The angular position of the motor rotor is measured by the Hall-effect sensors. The position information has a resolution of $360^\circ / (3 \times \text{number of motor poles})$ e.g. 20 degrees in a 6-pole motor. Angular position data provided by the torque sensor provides information about the angular position of the worm wheel on the steering shaft. When the
20 motor clutch is engaged, the motor is physically linked to the worm wheel through a worm and the clutch gearbox. Hence the angular position information from the torque sensor provides angular position information about the motor rotor. The angular position of the worm is known with respect to an arbitrary start position by resetting an offset to zero every
25 time a Hall sensor changes state, and the torque sensor provides position information relative to this arbitrary position, so absolute position of the motor can be determined.

By referencing the measured angular position of the motor to the
30 fixed angular position of a particular Hall-effect sensor transition (i.e.

commutation position), it is possible to calculate an absolute motor position with high accuracy. As long as the angular position from the torque sensor is referenced to the Hall-effect sensors on every commutation, it is possible to compensate for the effect of backlash in the gear box and for torsional wind-up in the worm and wheel under conditions of high load. A suitable torque sensor for providing the angular position information required is the Lucas linear array torque sensor or the eight channel sensor.

10 In another embodiment it is known that certain components of the motor torque ripple are predictable, being related to the angular position of the rotor. The high resolution absolute motor position information described above can be used to determine a correction to the demanded motor current in order to compensate for this ripple component. In this manner the ripple can be mapped out.

Additionally, by observing when a commutation event is signalled by the Hall effect sensors, a velocity value obtained from the last 2 high resolution absolute motor position readings can be used to calculate a delay time. For example, if a 2° advance angle is required then the velocity measurement can be used to determine how long it will take to travel 2° . This time delay can then be clocked by the control strategy and used to trigger the commutation event after the elapsed time. This proves most effective when the commutation point is close to the Hall effect signal.

It will be understood from the above description that in one of its aspects the present invention relates to an improved motor control strategy for an electric motor suitable for use in an EPAS system, in which two modulation techniques (drive modes) are employed depending on motor

conditions. In one mode, bottom-only modulation occurs, whilst in the other mode, complementary modulation occurs, the choice of drive mode being selected by a control algorithm. Several enhancements are also described to improve motor torque output. In this manner, considerable
5 improvements over a basic control strategy are effected, resulting in an improved torque output from the motor.

The improved motor control strategy is described in the context of a power steering application. It is, however, to be understood that the
10 control strategy is suitable for use in any application in which it is desirable to provide an improved torque output from an electric motor.

CLAIMS

1. A control strategy for controlling the pulse width modulation of a
5 multiple phase brushless motor 1 having at least three phases in which
each phase of the motor is connected to an arm of a multi-phase bridge
and each arm of the bridge comprises a top switching device 2,3,4 and a
bottom switching device 5,6,7, said switching devices comprising at least
one transistor,

10 characterised by said control strategy comprising driving the
switching devices 2,3,4,5,6,7 with a first modulation mode in which
complementary pulse width modulated inputs are applied to the top and
bottom switching devices in two arms of the bridge so that in each of said
two arms the top switching device is in the ON state whilst the bottom
15 device is on the OFF state, and at the end of the pulse width modulation
duty cycle the state of the two switching devices is reversed,

selection of said pulse width modulation duty cycle and which
switching devices are modulated being performed by a control algorithm
in response to the output of a sensing means.

20

2. A control strategy for controlling the pulse width modulation of a
multiple phase brushless motor 1 having three phases in which each phase
of the motor is connected to an arm of a multi-phase bridge and each arm
of the bridge comprises a top switching device 2,3,4, and a bottom
25 switching device 5,6,7, said switching devices 2,3,4,5,6,7, comprising at
least one transistor,

characterised in that said control strategy selects from a first
modulation mode and a second modulation mode:

whereby in said first modulation mode, the top switching device
30 and the bottom switching device in at least one arm of the bridge are

driven by complementary pulse width modulated inputs applied to the top and bottom switching devices so that one of the said top or bottom switching devices is in the ON state whilst the other one of the top or bottom switching device is in the OFF state, and at the end of the pulse width modulation duty cycle, the state of the two switching devices is reversed;

and whereby in said second modulation mode, a pulse width modulated input is applied to a bottom switching device in one of said arms of said bridge whilst a top switching device in a different one of said arms of said bridge is switched ON, selection of the pulse width modulation duty cycle and which switching devices are modulated being performed by a control algorithm.

3. A control strategy according to claim 2, in which complementary pulse width modulation inputs are applied to the top and bottom switching devices in two arms of the bridge when the first mode is selected, said two arms being the same two as the arms containing the bottom pulse width modulated switching device and the top ON switching device when the second modulation mode is selected.

4. A control strategy for a motor according to claim 2 or 3, in which the control algorithm switches motor drive from one of said modulation modes to the other at a motor current of approximately half the maximum motor current.

5. A control strategy for a motor according to any one of claims 2 to 4 in which a hard commutation mode or a soft commutation mode is employed.

6. A control strategy for a motor according to claim 5 in which soft commutation is implemented by decreasing the rate of decrease of the terminating phase current to match the rate of increase of the commencing phase current.

5

7. A control strategy for a motor according to claim 6 in which the duration of the soft commutation is determined by motor current and rotor position.

10 8. A control strategy for a motor according to claim 5 in which hard commutation is employed by increasing the rate of increase of the commencing phase current to match the rate of decrease of the terminating phase current.

15 9. A control strategy for a motor according to claim 8 in which the duration of the hard commutation is controlled by software.

10. A control strategy for a motor according to any preceding claim, in which the commutation position is varied by software by advancing or
20 retarding the position at which a commutation event occurs in response to motor position readings.

11. A control strategy for a motor according to any preceding claim, in which the sensing means comprises at least one current sensor for
25 detecting the current flowing in the motor and an angular position sensor for detecting the rotor position of the motor rotor.

12. A control strategy according to any preceding claim, in which the motor 1 is used in an EPAS system.

13. A method of calculating the position at a moment in time of a motor which is connected to an output shaft through an intermediate means by:

obtaining a first measurement of actual rotor position at a first
5 instance in time using sensing means provided at the motor;

calculating speed of rotation of said output shaft using a sensing means provided on said output shaft;

calculating an offset indicative of the displacement of the rotor of the motor between the first instance of time and said moment in time
10 based upon the speed of rotation of the output shaft, and;

modifying the first measurement of rotor position obtained at the first instance by adding the offset to produce an output indicative of absolute motor rotor position at said moment in time.

15 14. A method of calculating the position of a motor according to claim 13, in which both the sensing means on the output shaft and at the motor comprise angular position sensors.

15. A method of calculating the position of a motor according to
20 claim 13, in which the sensing means on the output shaft comprises a torque sensor which provides an output signal that is a function of angular position, and in which the sensing means at the motor comprises Hall effect sensors.

25 16. A method of calculating the position of a motor according to any one of claims 13,14 or 15, in which the output shaft comprises a steering column in an electrically assisted steering system, and in which the intermediary means comprises a clutch and/or a gearbox and/or a worm wheel and worm.

17. A method of calculating the position of a motor according to claim 14 or 15 in which output shaft speed is calculated by comparing an output from the angular position sensing means on the output shaft obtained at the said first instance in time with the output from said
5 angular position sensing means on said output shaft obtained at said moment in time.

18. A method of calculating the position of a motor according to claim 17, in which the speed of the motor rotor is obtained by multiplying the
10 output shaft speed by the gearbox ratio.

1/13

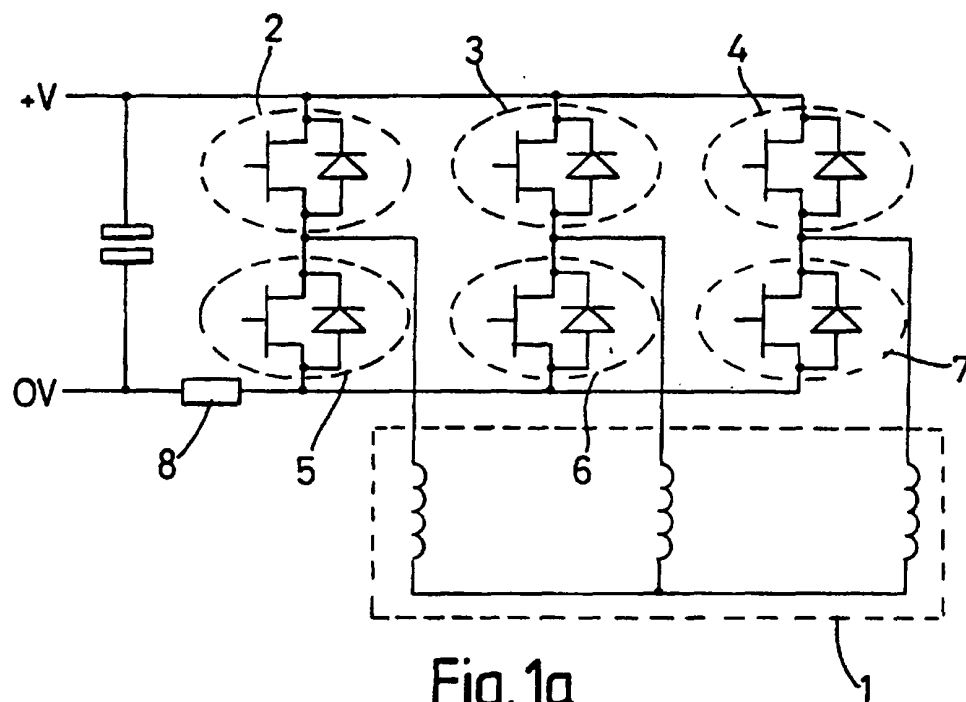


Fig. 1a

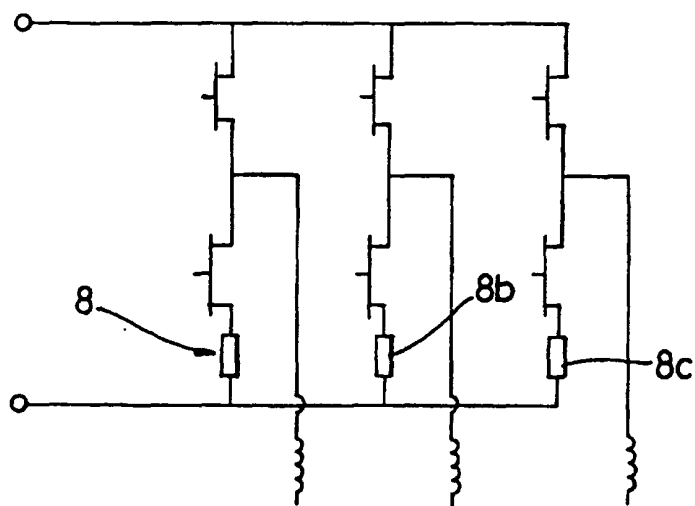


Fig.1b

2/13

Hall Sensor O/P Code			Drive Direct ⁿ	Red Phase FETs		Yellow Phase FETs		Blue Phase FETs	
A	B	C		Top	Bottom	Top	Bottom	Top	Bottom
1	1	0	FWD	OFF	OFF	OFF	PWM1	ON	OFF
1	0	0	FWD	OFF	PWM1	OFF	OFF	ON	OFF
1	0	1	FWD	OFF	PWM1	ON	OFF	OFF	OFF
0	0	1	FWD	OFF	OFF	ON	OFF	OFF	PWM1
0	1	1	FWD	ON	OFF	OFF	OFF	OFF	PWM1
0	1	0	FWD	ON	OFF	OFF	PWM1	OFF	OFF
1	1	0	REV	OFF	OFF	ON	OFF	OFF	PWM1
1	0	0	REV	ON	OFF	OFF	OFF	OFF	PWM1
1	0	1	REV	ON	OFF	OFF	PWM1	OFF	OFF
0	0	1	REV	OFF	OFF	OFF	PWM1	ON	OFF
0	1	1	REV	OFF	PWM1	OFF	OFF	ON	OFF
0	1	0	REV	OFF	PWM1	ON	OFF	OFF	OFF

Fig. 2

3/13

Hall Sensor O/P Code			Red Phase FETs		Yellow Phase FETs		Blue Phase FETs	
A	B	C	Top	Bottom	Top	Bottom	Top	Bottom
1	1	0	OFF	OFF	PWM2	PWM1	PWM1	PWM2
1	0	0	PWM2	PWM1	OFF	OFF	PWM1	PWM2
1	0	1	PWM2	PWM1	PWM1	PWM2	OFF	OFF
0	0	1	OFF	OFF	PWM1	PWM2	PWM2	PWM1
0	1	1	PWM1	PWM2	OFF	OFF	PWM2	PWM1
0	1	0	PWM1	PWM2	PWM2	PWM1	OFF	OFF

Hall Sensor Waveforms

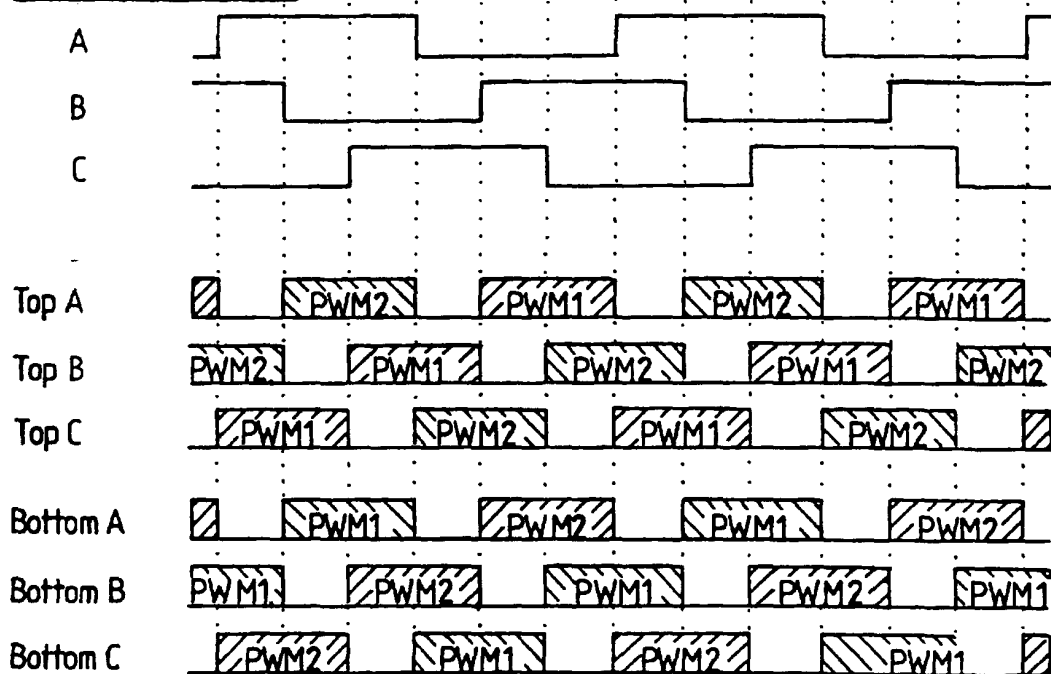


Fig. 3

4/13

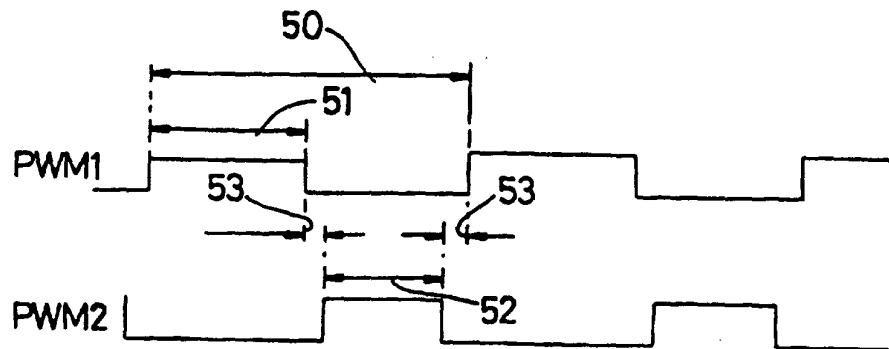


Fig. 4

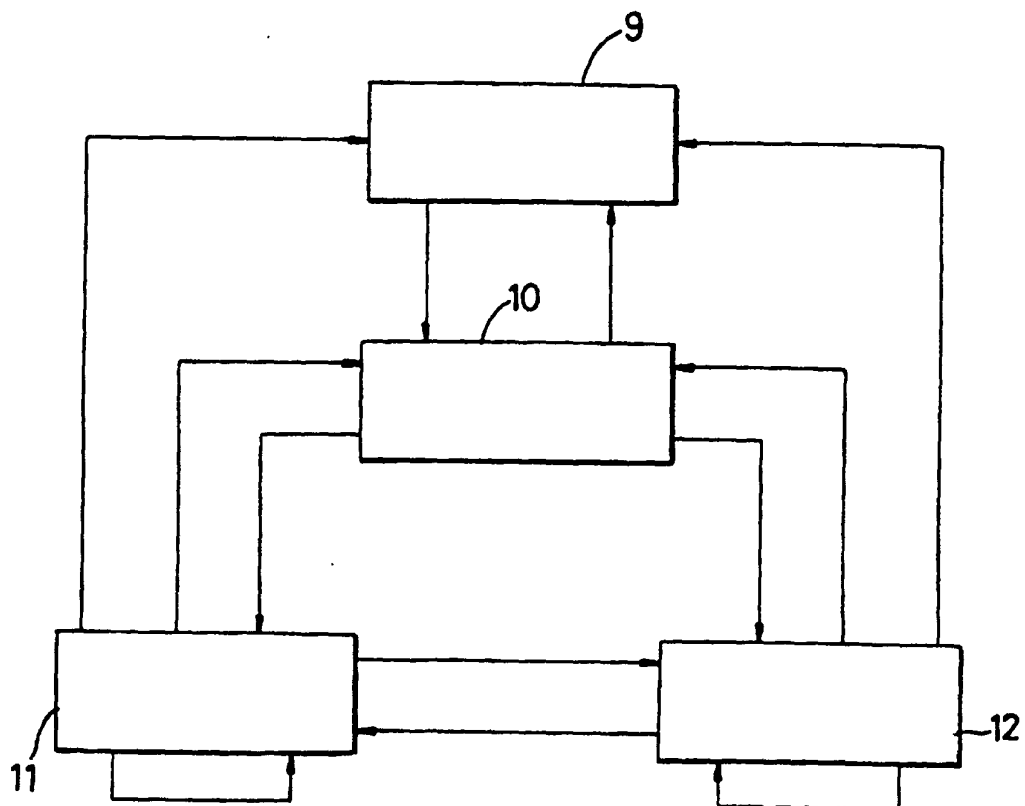


Fig. 5

SUBSTITUTE SHEET (RULE 26)

5/13

Motor Drive Direct ⁿ	Initial Hall Sensor Code				Final Hall Sensor Code		
	A	B	C		A	B	C
FWD	1	0	0	↑	1	0	1
FWD	1	0	1	↑	1	0	0
FWD	0	0	1	↑	0	1	1
FWD	0	1	1	↑	0	0	1
FWD	0	1	0	↑	1	1	0
FWD	1	1	0	↑	0	1	0
REV	1	1	0	↑	1	0	0
REV	1	0	0	↑	1	1	0
REV	1	0	1	↑	0	0	1
REV	0	0	1	↑	1	0	1
REV	0	1	1	↑	0	1	0
REV	0	1	0	↑	0	1	1

Fig. 6

6/13

Motor Drive Direct ⁿ	Initial Hall Sensor Code				Final Hall Sensor Code		
	A	B	C		A	B	C
FWD	1	1	0	⇓	1	0	0
FWD	1	0	0		1	1	0
FWD	1	0	1		0	0	1
FWD	0	0	1	⇓	1	0	1
FWD	0	1	1		0	1	0
FWD	0	1	0		0	1	1
REV	1	0	0	⇓	1	0	1
REV	1	0	1		1	0	0
REV	0	0	1		0	1	1
REV	0	1	1		0	0	1
REV	0	1	0		1	1	0
REV	1	1	0		0	1	0

Fig. 7

7/13

Hall Sensor O/P Code			Drive Direct ⁿ	Red Phase FETs		Yellow Phase FETs		Blue Phase FETs	
A	B	C		Top	Bottom	Top	Bottom	Top	Bottom
1	1	0	FWD	OFF	PWM2	OFF	PWM1	ON	OFF
1	0	0	FWD	OFF	PWM1	OFF	PWM2	ON	OFF
1	0	1	FWD	OFF	PWM1	ON	OFF	OFF	PWM2
0	0	1	FWD	OFF	PWM2	ON	OFF	OFF	PWM1
0	1	1	FWD	ON	OFF	OFF	PWM2	OFF	PWM1
0	1	0	FWD	ON	OFF	OFF	PWM1	OFF	PWM2
1	1	0	REV	OFF	PWM2	ON	OFF	OFF	PWM1
1	0	0	REV	ON	OFF	OFF	PWM2	OFF	PWM1
1	0	1	REV	ON	OFF	OFF	PWM1	OFF	PWM2
0	0	1	REV	OFF	PWM2	OFF	PWM1	ON	OFF
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0	1	0	REV	OFF	PWM1	ON	OFF	OFF	PWM2

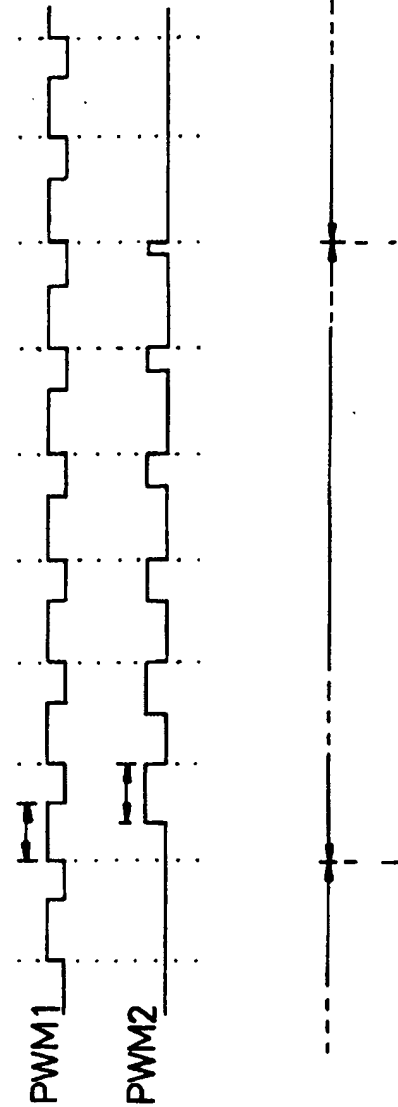


Fig. 8

8/13

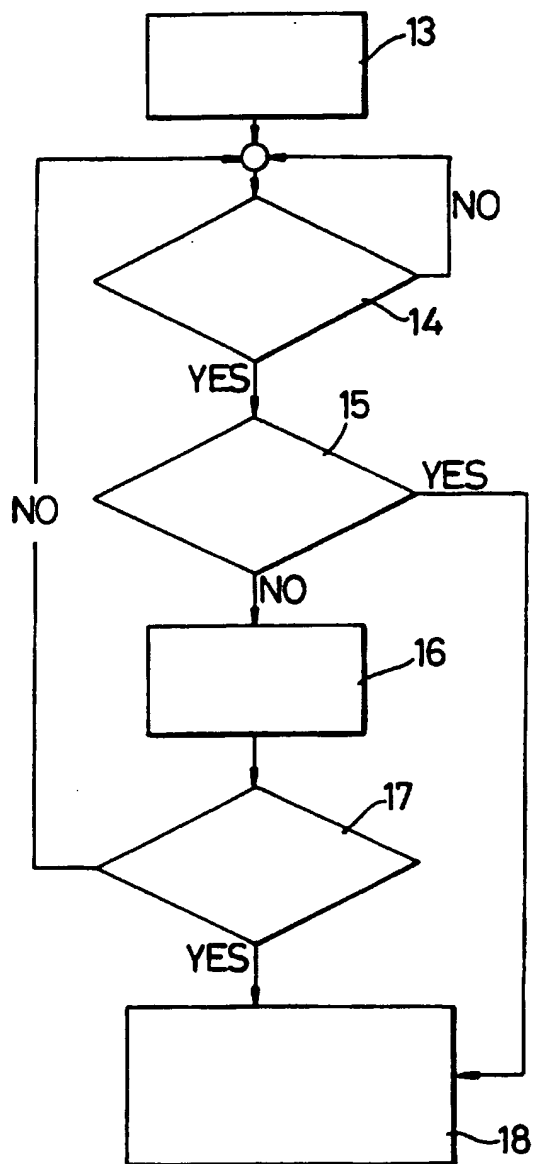


Fig. 9

9/13

Hall Sensor O/P Code			Drive Direct	Red Phase FETs		Yellow Phase FETs		Blue Phase FETs	
A	B	C		Top	Bottom	Top	Bottom	Top	Bottom
1	1	0	FWD	PWM2	OFF	OFF	PWM1	ON	OFF
1	0	0	FWD	OFF	PWM1	PWM2	OFF	ON	OFF
1	0	1	FWD	OFF	PWM1	ON	OFF	PWM2	OFF
0	0	1	FWD	PWM2	OFF	ON	OFF	OFF	PWM1
0	1	1	FWD	ON	OFF	PWM2	OFF	OFF	PWM1
0	1	0	FWD	ON	OFF	OFF	PWM1	PWM2	OFF
1	1	0	REV	PWM2	OFF	ON	OFF	OFF	PWM1
1	0	0	REV	ON	OFF	PWM2	OFF	OFF	PWM1
1	0	1	REV	ON	OFF	OFF	PWM1	PWM2	OFF
0	0	1	REV	PWM2	OFF	OFF	PWM1	ON	OFF
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0	1	0	REV	OFF	PWM1	ON	OFF	PWM2	OFF

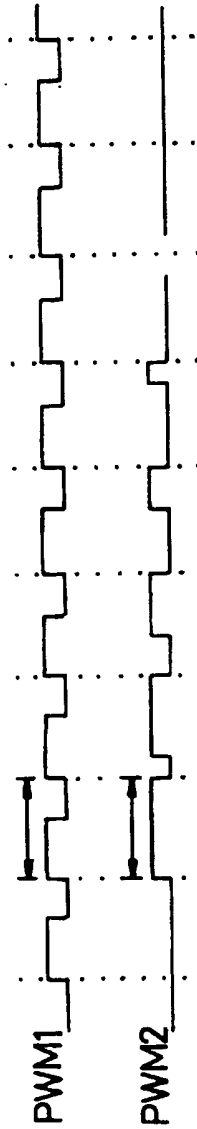


Fig. 10

10/13

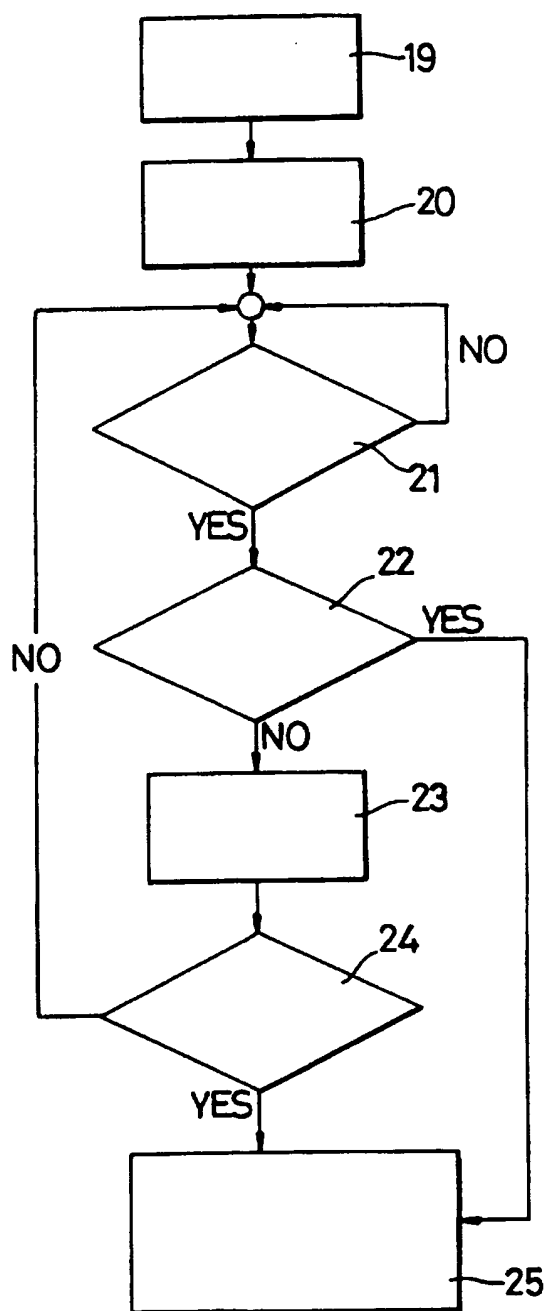


Fig.11

11/13

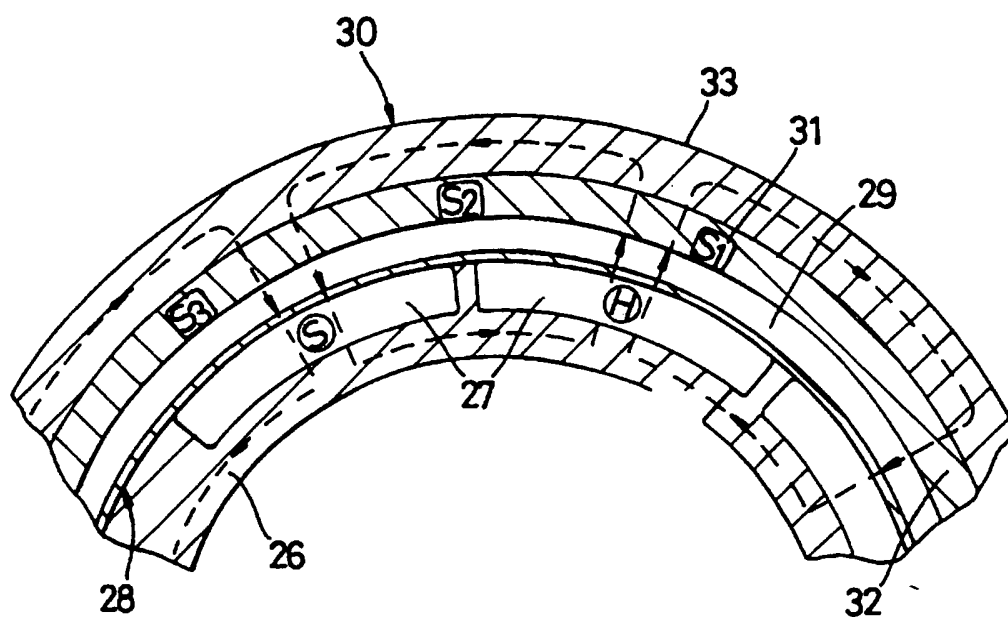


Fig.12

12/13

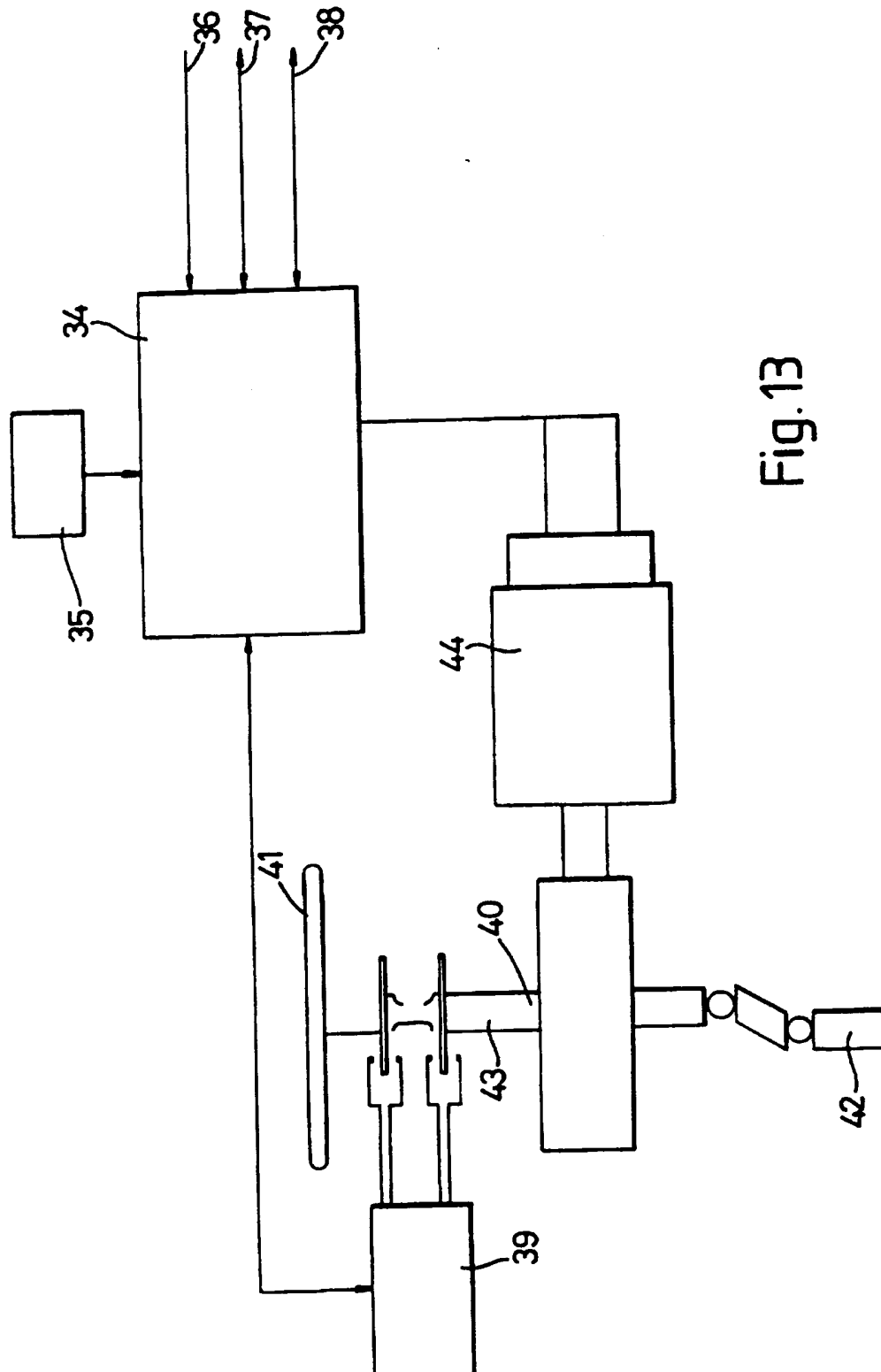


Fig.13

13/13

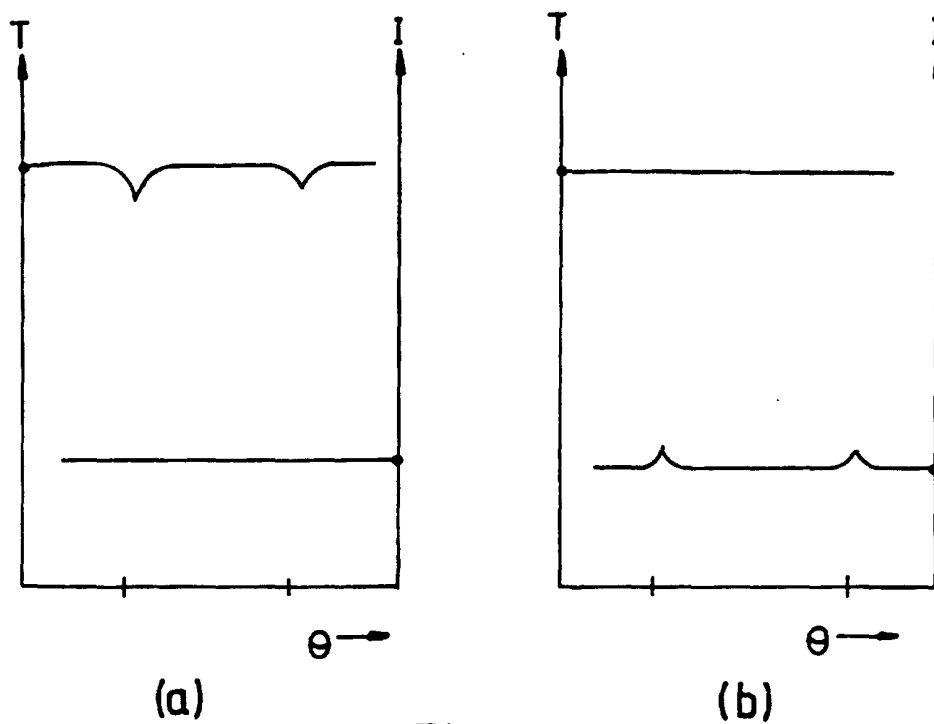


Fig.14

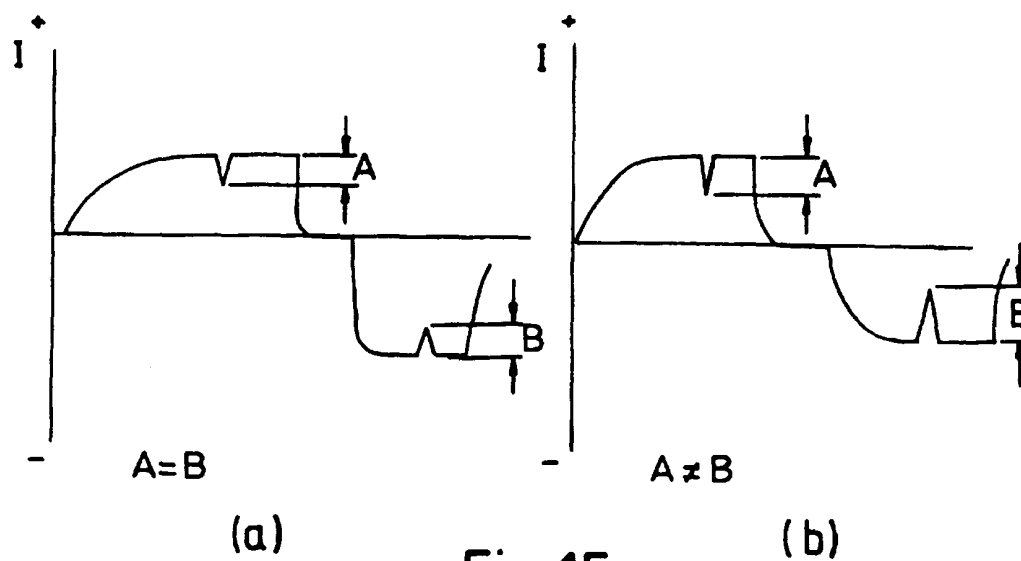


Fig.15

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 97/00052

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H02P6/08 H02P6/10

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H02P B62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 281 459 A (TOKYO SHIBAURA ELECTRIC CO) 1 March 1995 see abstract; figures 1,8 ---	1-12
A	US 5 463 300 A (OXIMBERG CAROL A) 31 October 1995 see abstract; figures 1,2 ---	1,2
A	EP 0 521 709 A (TOKYO SHIBAURA ELECTRIC CO ;TOSHIBA MICRO ELECTRONICS (JP)) 7 January 1993 see abstract; figure 1 ---	1,2
A	EP 0 599 260 A (KOYO SEIKO CO) 1 June 1994 see abstract; figure 5 -----	1,2,12

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

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- *A* document member of the same patent family

Date of the actual completion of the international search

2 April 1997

Date of mailing of the international search report

11.06.97

Name and mailing address of the ISA

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Authorized officer

BEYER, F

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. nal Application No

PCT/GB 97/00052

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 2281459 A	01-03-95	JP 7067381 A CN 1099532 A US 5491393 A	10-03-95 01-03-95 13-02-96
US 5463300 A	31-10-95	NONE	
EP 0521709 A	07-01-93	JP 5015157 A DE 69210487 D DE 69210487 T US 5373436 A	22-01-93 13-06-96 31-10-96 13-12-94
EP 0599260 A	01-06-94	JP 6211142 A US 5521475 A	02-08-94 28-05-96

INTERNATIONAL SEARCH REPORT

1. International application No.

PCT/GB 97/00052

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. CLAIMS: 1-12
2. CLAIMS: 13-18

FOR FURTHER INFORMATION PLEASE SEE FORM PCT/ISA/206 MAILED 16.04.97

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-12

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.